**sLHC Project Note 0003**

2009-07-13

Alessandra.Lombardi@cern.ch

# Summary of the workshop on HOM in SPL, held at CERN June 25-26.

A. Lombardi / BE-ABP, S.-H. Kim / ORNL, W. Weingarten / BE-RF

Keywords: SPL, HOM, dampers



## Scope of the workshop

A mini-workshop on the subject of HOMs in a superconducting proton linac was held at CERN on the 25th and 26th June 2009. The purpose of this workshop was to discuss more specifically the effects of HOMs on beam dynamics in the SPL and comparable accelerators and to provide guidelines for the specification of HOM dampers, if necessary.


## 1. Participation and agenda

The workshop had 25 registered participants, of which 10 participants from CERN. 10 institutions were represented (SNS, FNAL, ESS, TRIUMF, CNRS, CEA, IPJ, DESY, SCK-CEN and CERN).

The agenda with the link to the presentation is as follows:

**25th June**:

| | | |
|---|---|---|
| 14:00 | Welcome (05') | Roland Garoby (*CERN*) |
| 14:05 | Introduction (20') ( Slides ) | Roland Garoby (*CERN*) |
| 14:25 | The SPL case (20') ( Slides ) | Frank Gerigk (*CERN*) |
| 14:45 | HOMs (40') ( Slides ) | Joachim Tuckmantel (*CERN*) |
| 15:25 | Coffee break (30') | |
| 15:55 | Studies for the SPL at CERN (20') ( Slides ) | M. Schuh |
| 16:15 | Studies for the SPL at TRIUMF (20') ( Paper ; Slides ) | Rick Baartman (*TRIUMF*) , Joachim Tuckmantel (*CERN*) |
| 16:35 | Studies for the SPL at IPN Orsay (20') ( Slides ) | Jean-Luc Biarrotte (*IPN Orsay*) |
| 16:55 | Open points (55') | |

**26th June**

| | | |
|---|---|---|
| 09:00 | Experience at SNS (45') ( Slides ) | Sang-ho KIM (*ORNL*) |
| 09:45 | HOMs in high-energy part of the Project-X linac (30') ( Slides ) | Vyacheslav Yakovlev (*FNAL*) |

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|---|---|---|
| 10:15 | Coffee break (30') | |
| 10:45 | Experience at DESY (30') ( Slides ) | Rainer Wanzenberg (*DESY*) |
| 11:15 | Some aspects of HOM damping in 704 MHz BNL cavities (20') ( Slides ) | Rama Calaga (*BNL*) |
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|---|---|---|
| 14:00 | Experimental observation (1h00') ( Slides ) <br> Discussion topic | Sang-ho KIM (*ORNL*) |
| 15:00 | Dampers technical solutions (1h00') ( Slides ) <br> Discussion topic | Wolfgang Weingarten (*CERN*) |
| | | |
| 16:20 | Concluding remarks (40') | Alessandra Lombardi (*CERN*) |

## 2. The framework

In Table 1 the parameters of the Low Power SPL and the High Power SPL are reported.

**Table 1**

| | **LP-SPL** | **HP-SPL** |
|---|---|---|
| Kinetic energy | 4 GeV | 5 GeV |
| Beam power @4GeV | 0.14 MW | 3-8 MW |
| Repetition rate | 0.6-2 Hz | 50 Hz |
| Pulse length | 0.9 ms | up to 1.2 ms |
| Average pulse current | 20 mA | 0-40 mA |
| Proton pulse current | $1.1\ 10^{14}$ | $1.5\ 10^{14}$ |
| Length (SC linac) | 427 m | 502 m |

For HOMs with external Qs below $10^6$ the HOM voltage saturates during a single passage of the beam. For 50 Hz operation and an external Q > $10^8$ the HOM voltage increases from pulse to pulse and can reach significant values, while at a repetition of 2 Hz, the external Q must be above ~$10^9$ to reach comparable voltage levels. Between these “boundary values of Qext”, the HOM voltage does not saturate completely during the pulse, but still saturates completely from one pulse to another. Thus, for high values of Qext (HOM), the risk of beam distortion via HOMs is certainly larger for 50 Hz operation (HP-SPL). The design guideline is to design the SC cavities such that high repetition rates can be supported.

## 3. Effects of HOM

<u>Calculations tools</u>: 4 different, although not completely independent, codes have been used to calculate the SPL case. Two codes have been written at CERN and are used at CERN (called

JT and MS from the name of the authors). At TRIUMF calculations were made with the SNS code TALOBBU. Independent calculations done at IPN-Orsay were done with a code written by J-L B.

The two CERN codes and TALOBBU have been cross checked and they agree to the 5th decimal when using same input parameters. J-L B code agrees with JT for one case and it has not yet been extensively benchmarked against the others.

In general there is no doubt about the physics in the codes.

The debate during the workshop was mostly devoted to finding a set of coherent and reasonable input parameters for the calculation. The variety of parameters considered so far is such that depending on which safety factors are taken on the baseline parameters, opposite conclusions could be drawn. A list of the parameters discussed at the workshop and some preliminary conclusion on an agreed list of parameters for future simulations is reported.

*HOM frequencies*: it is agreed that the most dangerous frequencies are the machine lines (multiples of 352 MHz). Calculations with field solvers were presented (HFSS/ MAFIA). These programs show a fair agreement between each other and with measurements. In general HOMs can be excited at all frequencies provided there is a beam pattern that drives them (e.g. bunch charge fluctuations, transversely mis-steered beams, phase and energy jitter…).

*(r/Q)*Qext*: calculated (r/Q) Q ext and measured value can differ by a factor 10 [example M. Liepe measurements-presented by F Gerigk]. This effect could be explained by a different damping of the HOMs once the cavity is adjusted to have a flat field for the fundamental mode. Generally a safety factor of 10 has been taken for the current in the calculations, which has the same effect as taking a safety factor on $Q_{ext}$. In some of the simulation presented a r/Q independent of the particle velocity has been used. Agreement is that we need to use “effective r/Q” which includes the Transit Time Factor otherwise the effect of the induced voltage is overestimated.

*HOM frequency scatter:* the frequency scatter is a very important parameter in the calculations. The smaller the frequency scatter, the easier it becomes to excite HOMs. In the simulations, values between 0.1 and 1 MHz have been used. Based on the experience of other projects (SNS, TESLA, JLAB), the consensus is that a value of 1-2 MHZ is more realistic, as a result of manufacturing errors.

*Beam current pulse-to-pulse variation:* a very critical parameter, as it is one of the drivers of HOM instabilities for frequencies outside of machine lines. Wide band measurements from the source are very difficult and values between 10 % and 1 % have been used in the simulations. Measurements from the ISIS source and measurements from the SNS source don’t seem to agree on a pulse-to-pulse stability value but possibly the interpretation is not clear. In any case there is a general agreement that 10% is excessive and that a value of 1-3% is more realistic.

Table 2 summarizes the parameters for the next simulations agreed at the workshop.

**Table 2**

| | |
|---|---|
| Beam Intensity | 40 mA |
| Intensity pulse-to-pulse jitter | 1-3% |
| r/Q | Take nominal and keep into account the effect of beam velocity |
| Frequency spread | 1-2 MHz |

Other effects to be included as drivers of HOM are:

- Variable chopping pattern and partially deflected bunches

- Transverse alignment errors

*HOM power*: the case was not thoroughly presented for the SPL, but simulations have been done and data exists [https://edms.cern.ch/document/978828/1]. The potentially high value of the HOM power has been the reason behind the decision to equip each cavity with two dampers in the SNS accelerator. Simulation of the case of FNAL Project X shows that there is an effect only for an alternative linac design that would run CW.

## 4. Experience from other labs

SNS: During the design study, calculations didn't show any beam dynamics issues for values of Qext up to $10^8$. However, the decision was taken in 2000 to equip every cavity with two HOM dampers to avoid the potential risk of excessive heat dissipation. At the time no experience on a pulsed superconducting proton linac was available. During the first years of operation, the dampers caused problems due to multipacting at the RF frequency and no sign of beam degradation induced by HOMs was observed. Hence, the feed-throughs of the dampers have been progressively removed (the coupler remains as an integral part of the cavity). Furthermore it was found that the HOMs couple to the steel bellows between the cavities, which already provides a damping that reduces the Qext of all relevant HOMs below $10^7$. The experience from SNS would favor the choice of not having dampers in the SPL, unless some fundamental difference in the beam dynamics appears due- possibly- to the different number of cavities, (81 SNS vs. 234 SPL), to a different chopping pattern or to the potential use of the SPL as electron re-circulator.

DESY: TESLA, FLASH 9-cell cavities are equipped with dampers. They work well and they are needed. The context of an e-collider is different, due to the stringent beam dynamics requirement on the beam centre position. It seems unlikely that SPL should have the same strict beam dynamics requirements in any of its future potential use. It is nevertheless recommended to check that transverse modes don't degrade significantly the beam dynamics.

## 5. Summary/conclusions of the workshop

It was agreed that new simulations of the SPL case with the parameters shown in Table 2 should be performed before taking any conclusion on the need of HOM dampers. Heat dissipation because of HOMs shall also be evaluated.

The possibility to use a design similar to SNS, with the inter-cavity connections (bellows) providing sufficient HOM damping, shall be studied carefully. Should this not be sufficient in view of the results of the next simulations, a careful design (or possibly a test) of a sound technical solution for a damper shall be studied. Steps in this direction were presented during the discussion on "dampers technical solutions".

It was also agreed that, because of the variety of potential future uses of the SPL, the superconducting cavities should be equipped with ports to allow both HOM monitoring as well as the possibility of adding dampers at a later stage. The design of these ports shall be part of the overall cavity design handled by the cavity working group.

## 6. Discussion session on “experimental observation”, by Sang-Ho Kim

During this discussion session it was agreed that the next thing to do is to set reasonable input conditions for the SPL simulation. Based on other experiences one could envisage to find that:

- Mild beam dynamics issue
- Mild damping requirement
- Mild HOM power issue
- (Passive damping + FPC coupling) would be enough for the initial stage of SPL
- System integrity/soundness/healthiness should be the first concern

Nevertheless it was agreed that it’s best to have some rooms for the HOM coupler for the future in case of:

- Unexpected mode
- Electron acceleration
- Beam time-structure variation (chopping)
- R&D for the reliable HOM coupler

## 7. Discussion session on “dampers technical solutions”, by Wolfgang Weingarten

W. Weingarten presented some topics for discussion that need addressing before a HOM dampers is designed. His presentation was mainly based on a paper by E. Haebel, “Couplers for cavities”, published in the CERN Yellow Report CERN-96-03.

1. HOM spectrum: The spectrum is known for the SPL $\beta$=1 geometry presently under study (M. Schuh’s presentation). The HOMs possessing a significant interaction with the beam (high R/Q) cluster around only few frequency bands: TE111, TM110 and TM011.

2. Upper tolerable limit for $Q_{ext}$ from the beam break up point of view: The answer can be found in the talks of M. Schuh, J.-L. Biarotte, R. Baartman, J. Tuckmantel. Notwithstanding further more complete simulations, a $Q_{ext}$ of $10^6 – 10^8$ seems tolerable.

3. Worst case maximum tolerable RF power absorbed by the HOM coupler: this situation may occur if the machine line coincides with one of the frequencies of HOMs with a high R/Q. The cavity geometry should be chosen in such a way to avoid this situation.

4. The most elegant solution would consist in using the cut-off features of the beam tubes in such a way as to confine the fundamental mode and possibly unavoidably a few HOMs and to let pass into the beam tubes all other HOMs to be damped there. However, possible trapped modes must be identified and eliminated by a suitable choice of the cavity geometry.

5. The next but less elegant solution would consist in a tapered beam tube (not necessary symmetric for both cavity ends) with a bigger diameter close to the cavity to house the power coupler and a smaller diameter further off providing sufficient damping to the

fundamental and less or no damping to the HOMs. The HOM power may propagate still further into the connection bellows between cavities. That part of the beam tube with the smaller diameter may be equipped with ports that may take antenna type HOM coupler (without notch filter) in case they are needed (c.f. scheme below). During the discussion no fundamental objections were raised concerning this idea.